

Parachute Seminar

3rd International Planetary Probe Workshop

Aerodynamics II (Unsteady)

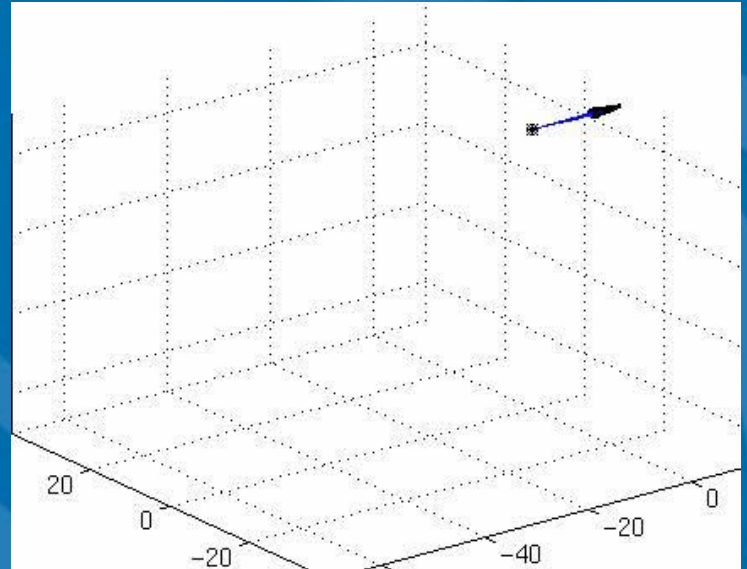
Steve Lingard

Vorticity Ltd

steve.lingard@vorticity-systems.com

Unsteady Flow

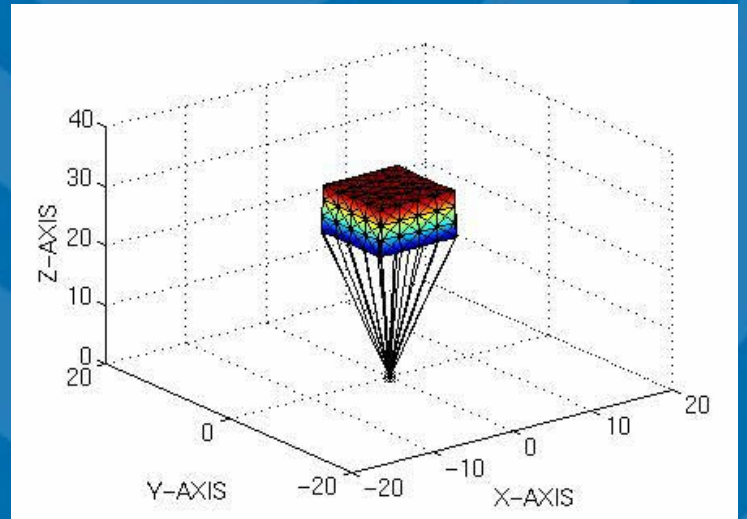
- ◆ Inflation



- ◆ Dynamics

- ◆ Oscillation

- ◆ Acceleration



Dimensionless Parameters In Unsteady Flow

$$\frac{m_s}{\rho D_o^3} \text{ mass ratio } (M_r)$$

$$\frac{V^2}{g D_o} \text{ Froude number } (F_r)$$

$$\frac{Vt}{D_o} \text{ dimensionless time } (\tau)$$

Mass Ratio - $\frac{m_s}{\rho D_o^3}$

- ◆ The ratio of the payload mass to a representative air mass
- ◆ Important in:
 - ◆ Inflation
 - ◆ wake recontact
 - ◆ parachute dynamics

Froude Number - $\frac{V^2}{gD_0}$

- ◆ Ratio of fluid inertial forces to gravitational forces
- ◆ Selection of velocity important

Steady descent velocity (V_T) $\frac{1}{2}\rho V_T^2 C_D S_0 = m_s g$

$$V_T^2 = m_s g / k \rho D_0^2$$

where k is a constant $\pi C_D / 8$

$$F_r = \frac{1}{k} \cdot \frac{m_s g}{\rho D_0^2} \cdot \frac{1}{D_0 g} = \frac{1}{k} \cdot \frac{m_s}{\rho D_0^3}$$

i.e. is equivalent to mass ratio

Froude number is defined using lines taut velocity V_s and represents inflation initial conditions

Dimensionless Time - $\frac{Vt}{D_o}$

- ◆ Relates time interval to characteristic time for parachute

- ◆ Lines taut velocity used $\tau = \frac{V_{st}}{D_o}$

- ◆ Important in inflation modelling τ is approximately constant for a given parachute

Added Mass

- ◆ Also called “virtual mass” and “apparent mass”
- ◆ When body accelerated in a fluid $a < F/m$
- ◆ Fluid must also be accelerated
- ◆ Added mass $\alpha = \delta F/a$
- ◆ Important for
 - ◆ airships
 - ◆ submarines
 - ◆ parachutes
- ◆ Exists for all bodies moving in a fluid
 - ◆ For accelerating and steady flow
 - ◆ For inviscid and viscous fluids

Added Mass

LS-DYNA USER INPUT
Time = 0.008991
Vector of Total-velocity
min=0, at node# 1555
max=35.389, at node# 252406

Fringe Levels

4.000e+01
3.600e+01
3.200e+01
2.800e+01
2.400e+01
2.000e+01
1.600e+01
1.200e+01
8.000e+00
4.000e+00
0.000e+00

z
x

LS-DYNA USER INPUT
Time = 0.024999
Vector of Total-velocity
min=0, at node# 1555
max=40.2257, at node# 60777

Fringe Levels

4.000e+01
3.600e+01
3.200e+01
2.800e+01
2.400e+01
2.000e+01
1.600e+01
1.200e+01
8.000e+00
4.000e+00
0.000e+00

z
x

Added Mass

Can be expressed in terms of kinetic energy

$$T_{body} + T_{fluid} = \frac{1}{2} V^2 \left[m + \rho \iiint (\bar{U}/V)^2 d\forall \right]$$

Added mass term is

$$\alpha = \rho \iiint (\bar{U}/V)^2 d\forall = 2T_{fluid} / V^2$$

For inviscid flow it is function only of body shape and direction of motion

For viscous flow is also function of the history of the motion due to the wake

Added Mass

For translation velocity components (V_1, V_2, V_3)
and rotation components (V_4, V_5, V_6)

$$2T_{fluid} = \sum_{i,j} a_{ij} V_i V_j$$

i.e. a 36 component tensor

for inviscid flow: $a_{ij} = a_{ji}$

added mass coefficients are defined as: $k_{ij} = \frac{a_{ij}}{\rho \nabla}$

where ∇ is an appropriate reference volume

Added Mass

For a hemispherical shell $a_{11} = 2.136\rho\frac{\pi D_p^3}{12}$

For a 90kg load descending under a 6.7m projected diameter parachute at low earth altitude,

$$a_{11} = 2.136 \times 1.225 \times \frac{\pi \times 6.7^3}{12} = 206\text{kg}$$

added mass greater than payload mass

**ADDED MASSES MUST BE USED
IN DYNAMIC MODELLING**

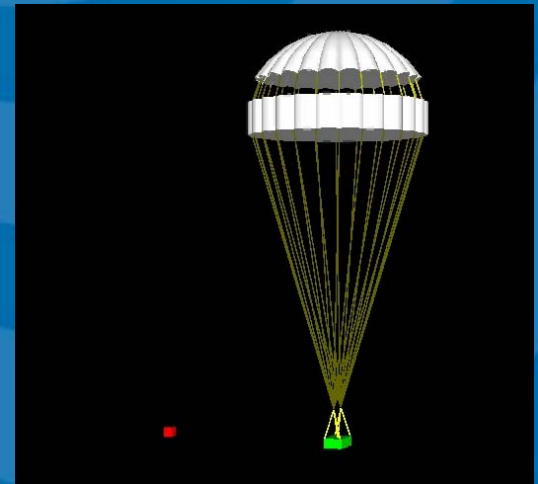
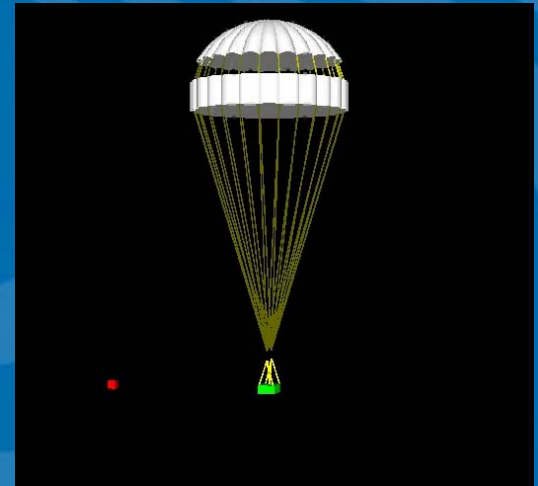


Added Mass

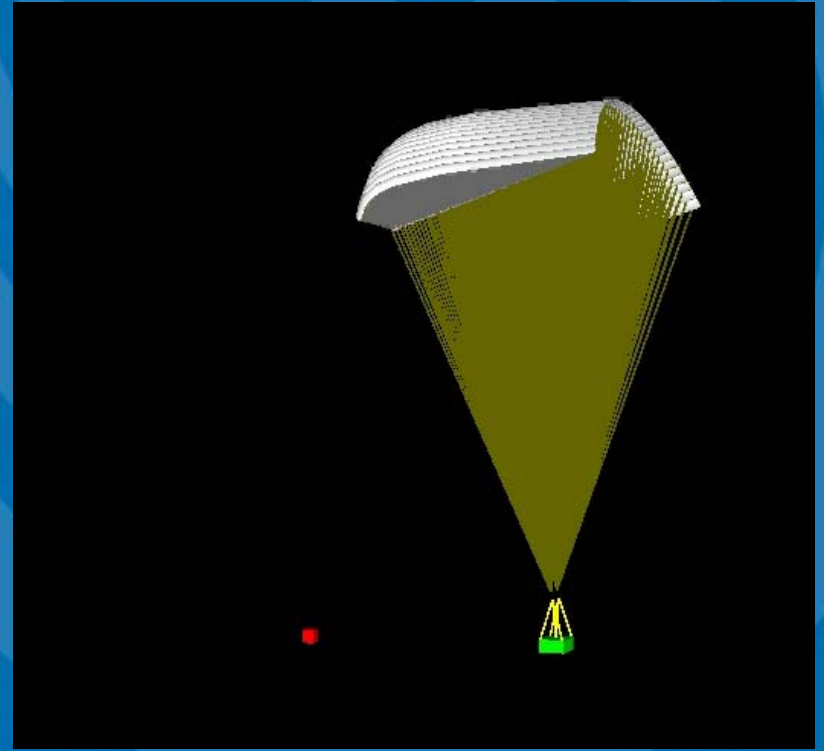
Do (m)	Earth (kg)	Mars (kg)
1	0.22	0.00
3	5.82	0.04
10	215.39	1.58
30	5815.63	42.73

Added Mass

- ◆ For low density atmospheres added mass is small – leads to surprising effects for those used to terrestrial parachute performance
 - ◆ High added mass disguises instability
 - ◆ Glide
 - ◆ Unstable parachutes exhibit unacceptable dynamics in low density environment



Added Mass



Added Mass

Unsteady force is represented by: $F(t) = \frac{1}{2} \rho C_d^u A |U(t)| U(t) + \rho k_{ij}^u \nabla \frac{dU(t)}{dt}$

For oscillatory motion of period T with time dependent velocity

$$U(t) = \hat{U} \sin(2\pi t / T)$$

The coefficients are functions of:

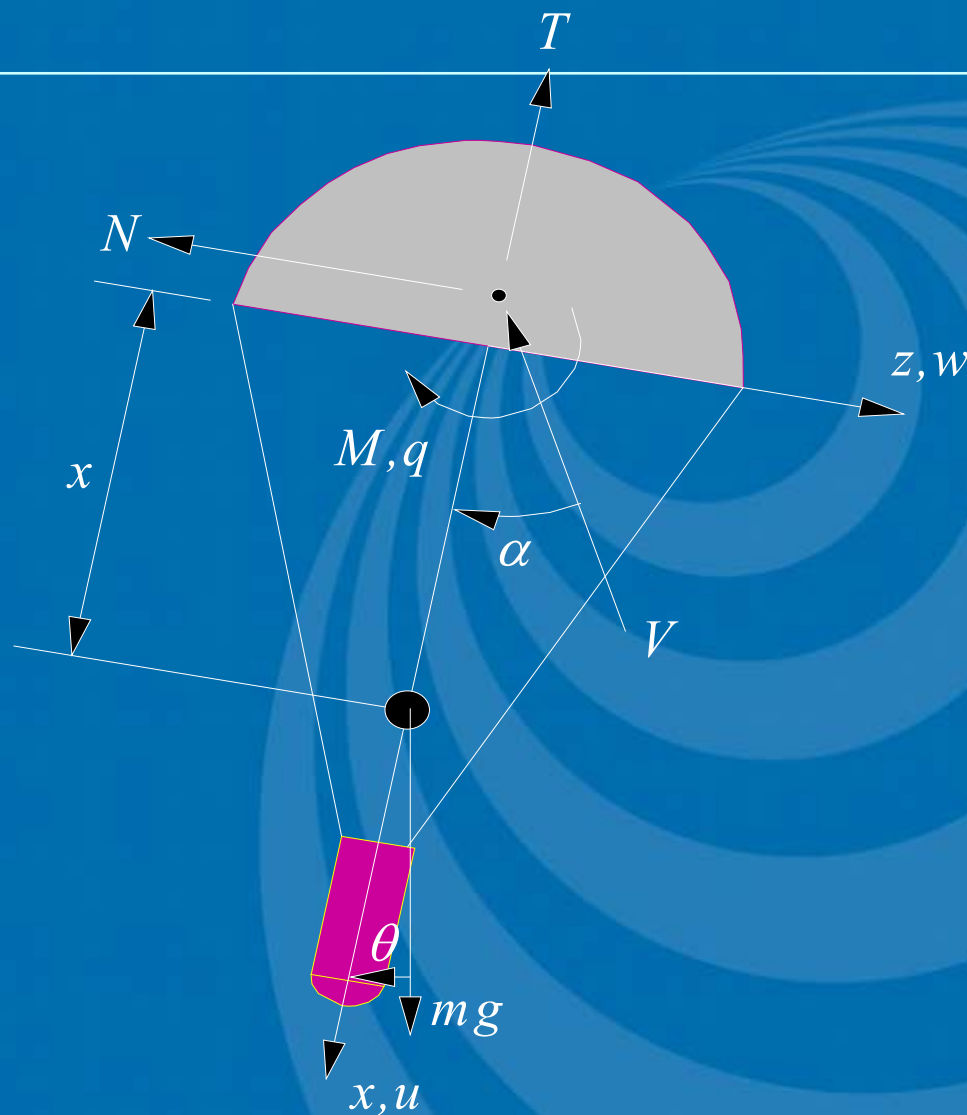
- Reynolds number
- Mach number
- Keuligan-Carpenter number

$$K_C = \frac{\hat{U}T}{D}$$

Added Mass

For small Keuligan-Carpenter number

- ◆ unsteady drag coefficient tends to steady value
- ◆ added mass coefficient tends to inviscid value
- ◆ For parachutes this is usually true



System of axes and definition of terms for a descending parachute

Equations of Motion

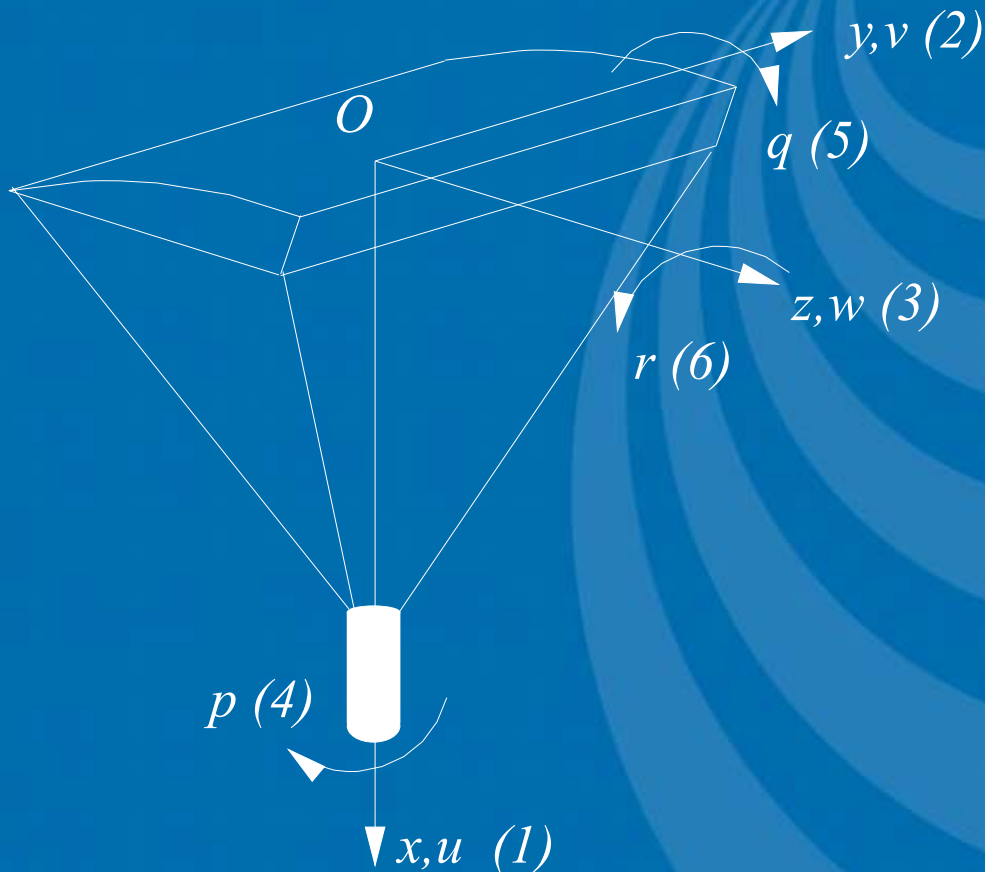
$$X = (m + a_{11})\dot{u} + a_{13}\dot{w} + a_{15}\dot{q} + (m + a_{33})wq + a_{13}uq + (a_{35} - mx)q^2$$

$$Z = (m + a_{33})\dot{w} + a_{13}\dot{u} + (a_{35} - mx)\dot{q} - (m + a_{11})uq - a_{13}wq - a_{15}q^2$$

$$M = (mx^2 + I + a_{55})\dot{q} + a_{15}(\dot{u} + wq) + (a_{35} - mx)(\dot{w} - uq) + (a_{11} - a_{33})uw \\ + a_{13}(w^2 - u^2)$$

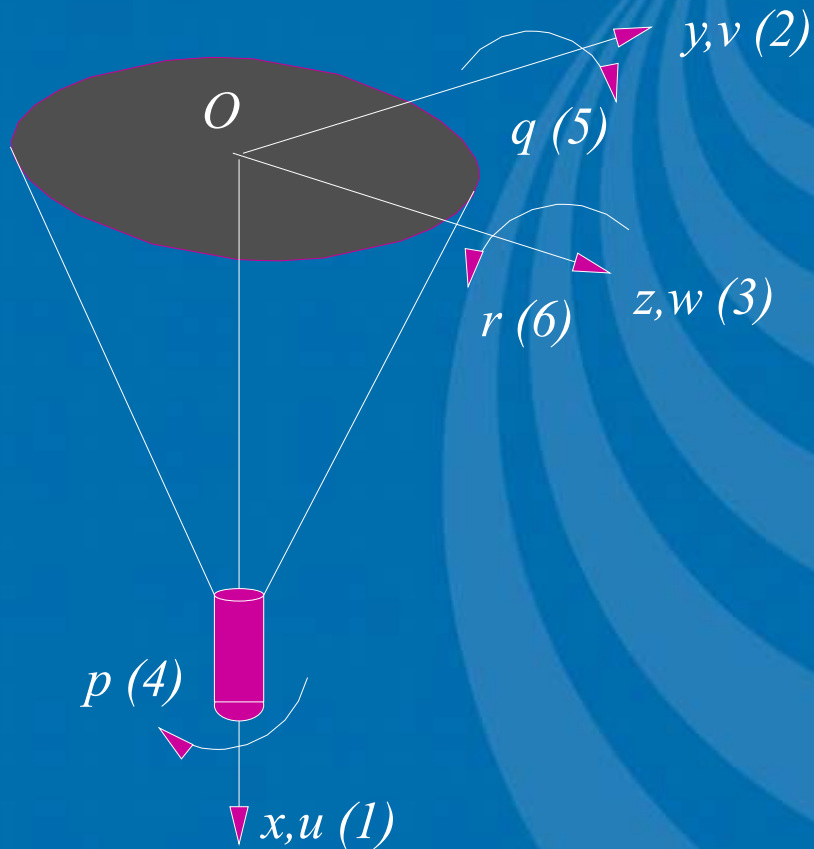


Added Masses For A Single Plane Of Symmetry



$$\begin{array}{cccccc}
 a_{11} & 0 & a_{13} & 0 & a_{15} & 0 \\
 & a_{22} & 0 & a_{24} & 0 & a_{26} \\
 & & a_{33} & 0 & a_{35} & 0 \\
 & & & a_{44} & 0 & a_{46} \\
 & & & & a_{55} & 0 \\
 & & & & & a_{66}
 \end{array}$$

Two Planes of Symmetry

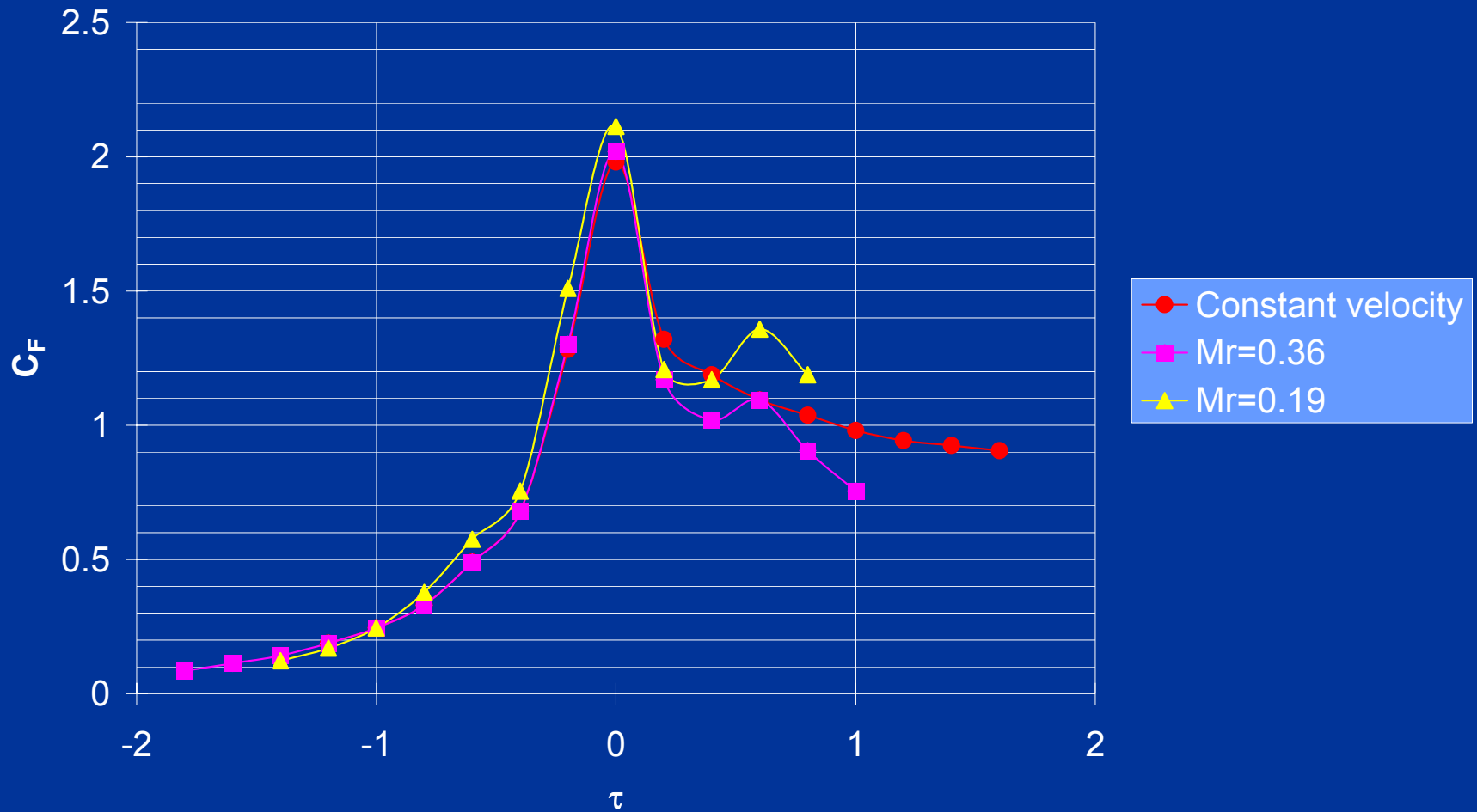


$$\begin{array}{cccccc}
 a_{11} & 0 & 0 & 0 & 0 & 0 \\
 & a_{22} & 0 & 0 & 0 & a_{26} \\
 & & a_{33} & 0 & a_{35} & 0 \\
 & & & a_{44} & 0 & 0 \\
 & & & & a_{55} & 0 \\
 & & & & & a_{66}
 \end{array}$$

Rotational Symmetry

- ◆ For a circular parachute
 - ◆ $a_{22} = a_{33}$, $a_{55} = a_{66}$, $a_{44} = 0$
 - ◆ $a_{35} = a_{26}$ and are small
- ◆ Only 3 coefficients to determine

Inflation

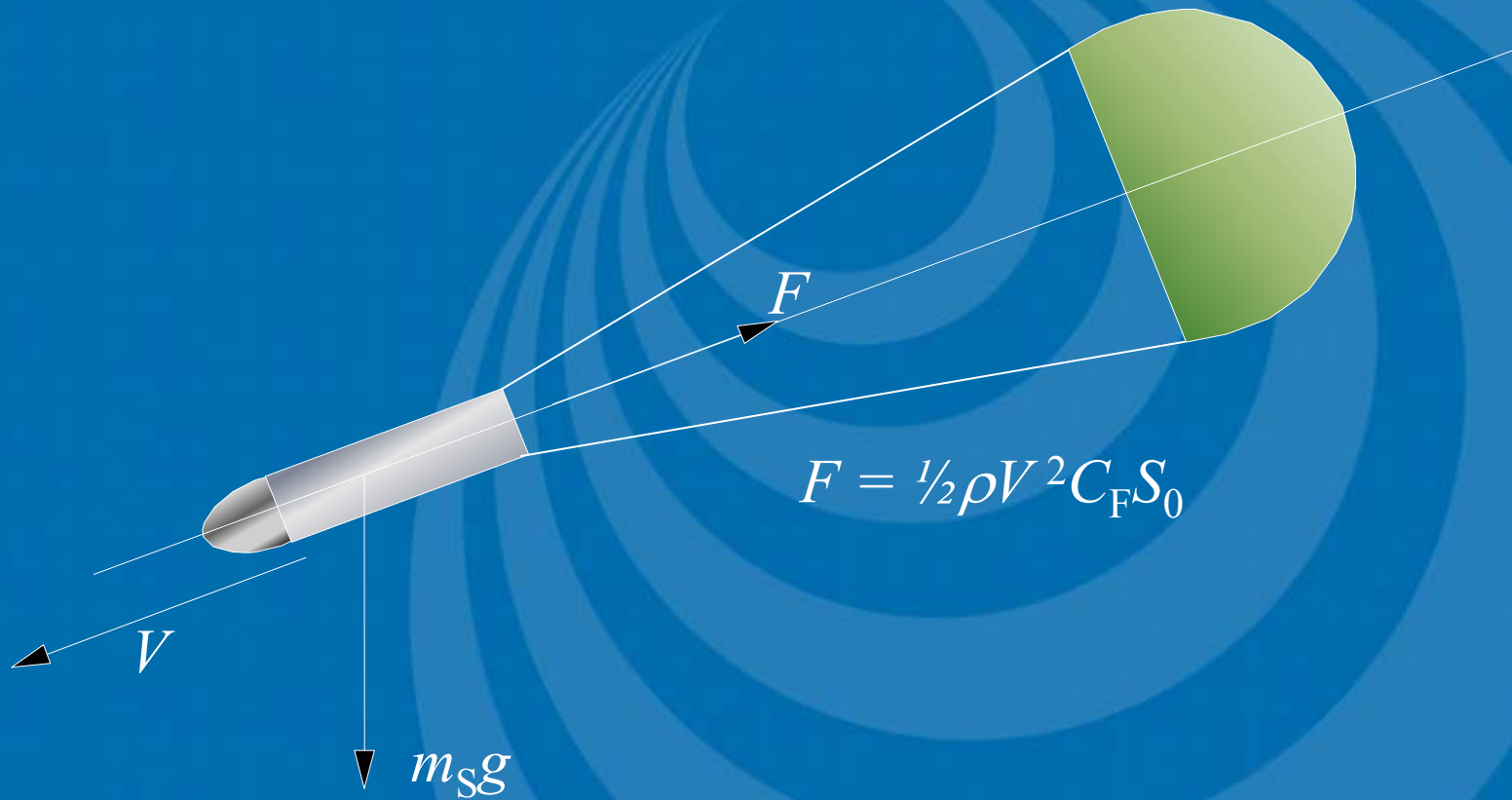


Inflation

force coefficient $(C_F = F / qS_o)$

dimensionless time $(\tau = V_S(t - t_i) / D_o)$

- ◆ force coefficient is independent of mass ratio and Froude number and is a function only of dimensionless time
- ◆ inflation time occurs in a fixed dimensionless time $(\tau_o = V_S t_i / D_o)$



Schematic diagram of inflating parachute

Equation of Motion

$$m_s \frac{dV}{dt} = -\frac{1}{2} \rho V^2 S_o C_F(\tau)$$

where $\tau = \frac{V_S}{D_o}(t - t_i)$

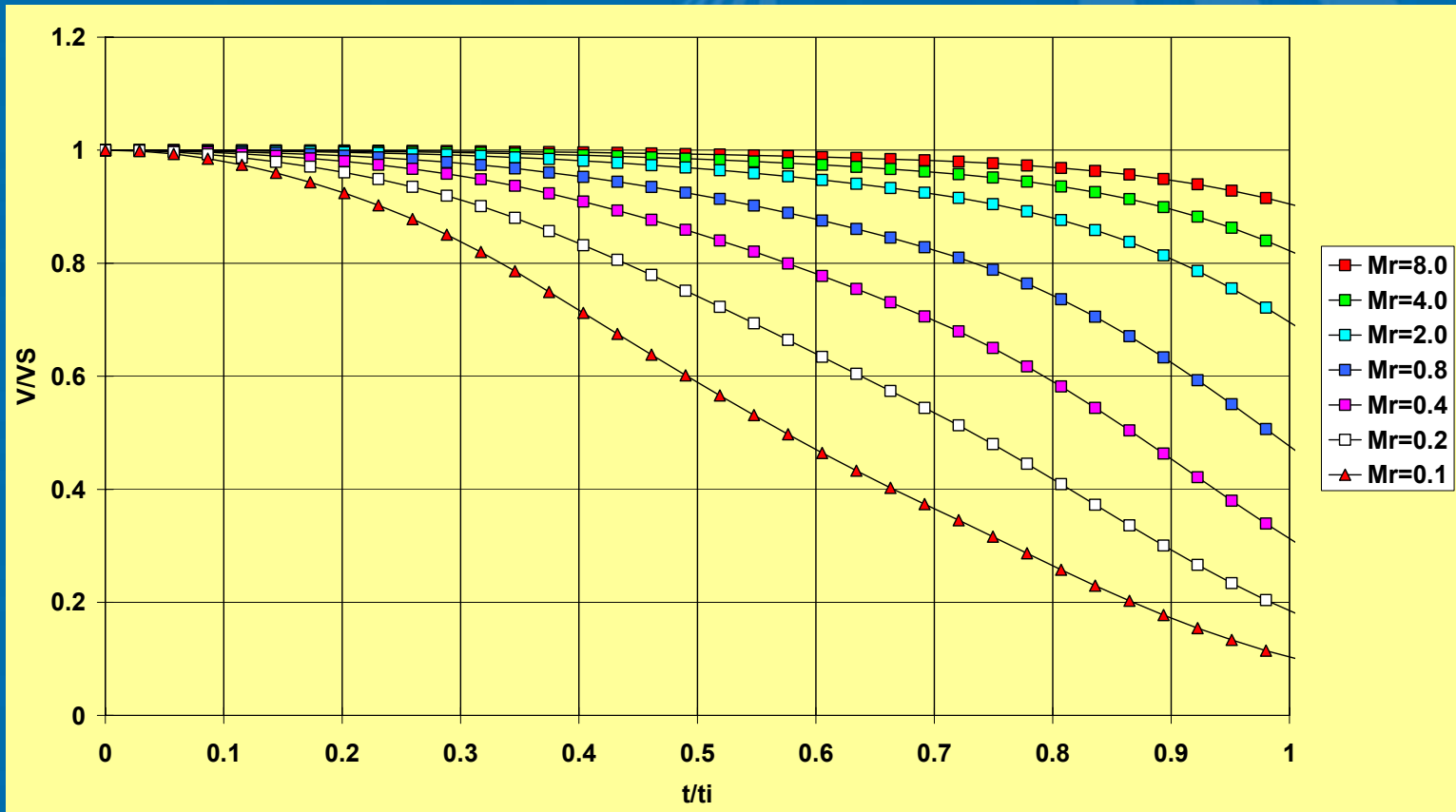
re-arranging $\int_{V_S}^V \frac{dV}{V^2} = -\frac{1}{2} \rho \frac{S_o D_o}{m_s V_S} \int_{\tau_0}^{\tau} C_F(\tau) d\tau$

solving $\frac{1}{V} = \frac{1}{V_S} + \frac{1}{2} \rho \frac{S_o D_o}{m_s V_S} \int_{\tau_0}^{\tau} C_F(\tau) d\tau$

therefore $\frac{V}{V_S} = \left[1 + \frac{\pi}{8 M_r} \int_{\tau_0}^{\tau} C_F(\tau) d\tau \right]^{-1}$

Thus $V = V_S f(M_r, \tau)$

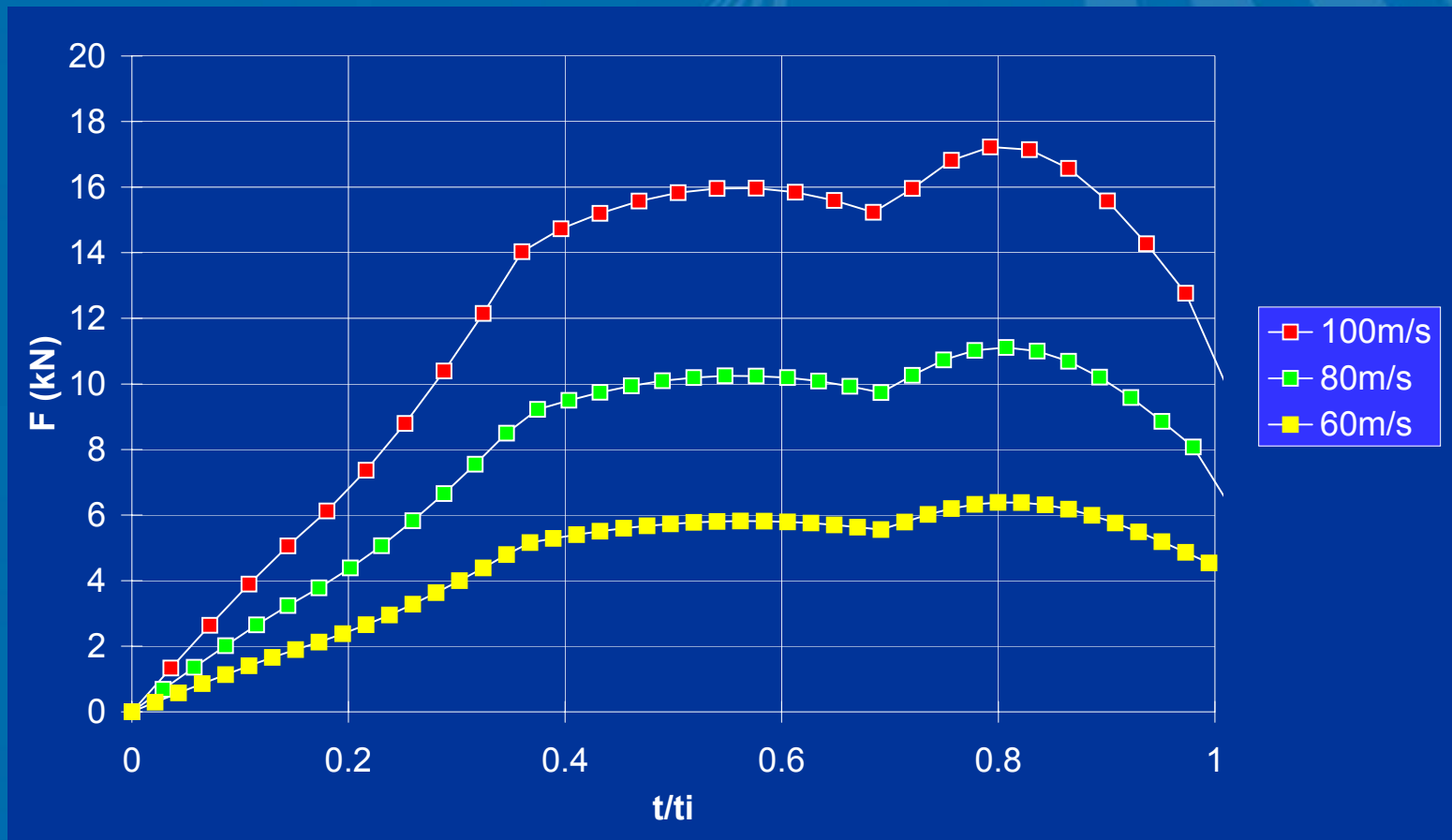
Velocity ratio is a function of mass ratio



Velocity ratio versus time ratio for flat circular parachute

The force acting on the payload may be written
$$F = \frac{1}{2} \rho V_s^2 \left[f(M_r, \tau) \right]^2 S_o C_F(\tau)$$

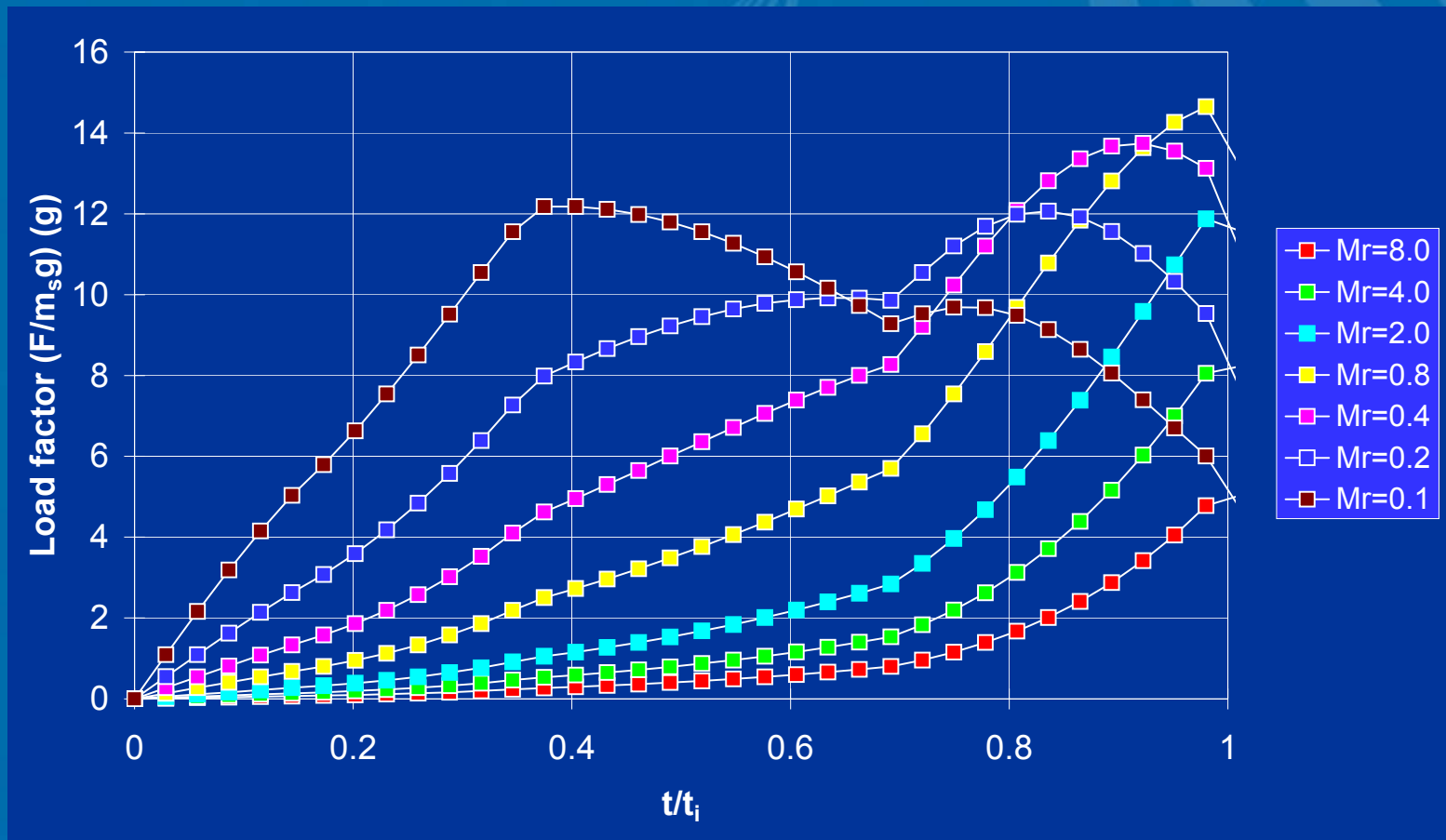
Force amplitude proportional to V^2



Flat circular parachute inflation force as a function of initial velocity

Consider now the load factor: $\frac{F}{mg} = \frac{V_s^2}{D_0 g} \cdot \frac{\pi}{8M} \cdot [f(M, \tau)]^2 G(\tau)$

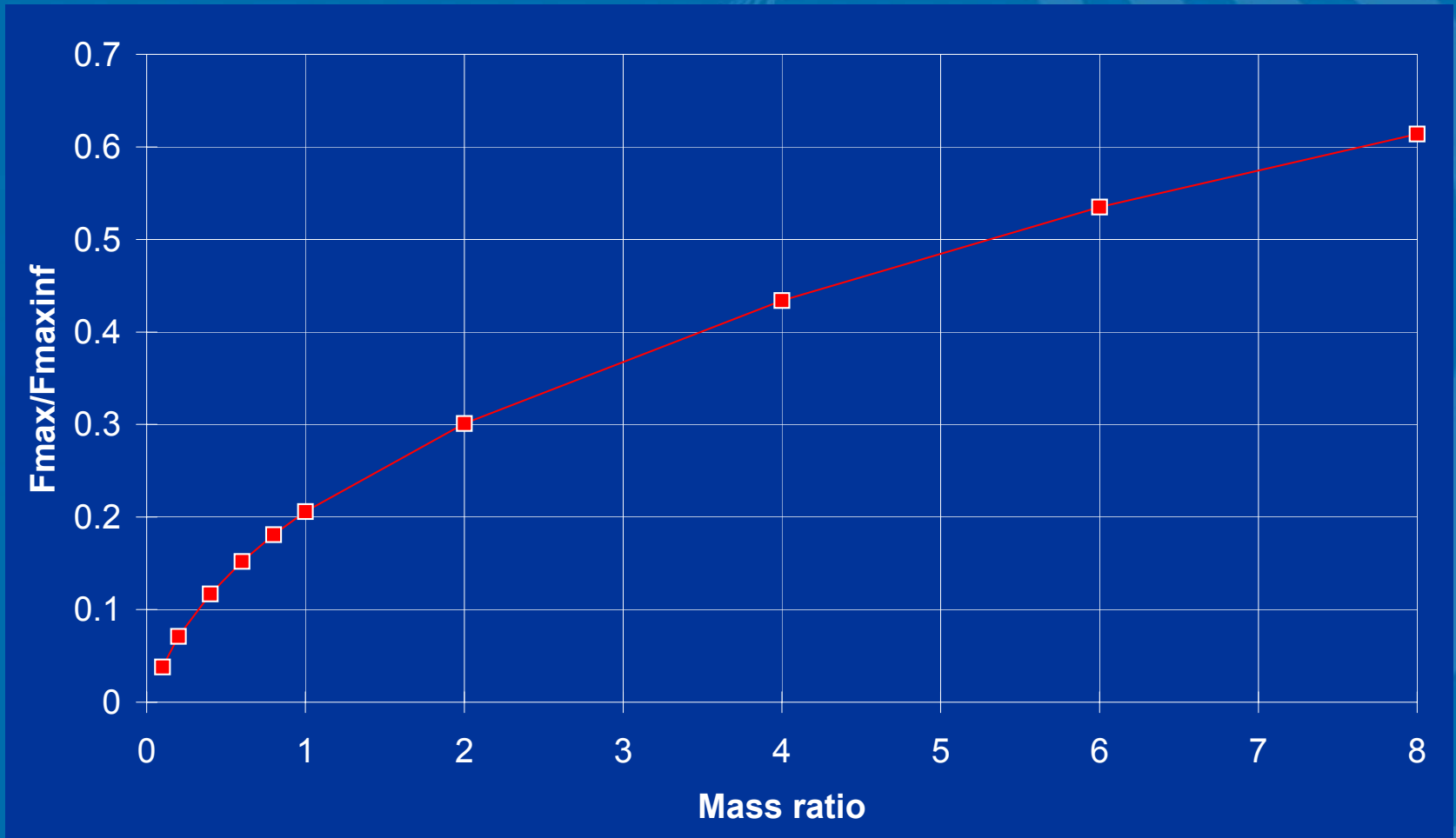
Shape of inflation curve determined by mass ratio



Load factor for flat circular parachute as a function of mass ratio (Fr= 76.4)

Maximum inflation force to infinite mass force

$$\frac{F_M}{F_{M\infty}} = \frac{[f(M_r, \tau)]^2 C_F(\tau)}{C_F(\tau_0)}$$



Inflation

- ◆ Mass ratio determined the shape of the inflation force curve
- ◆ Froude number determines the amplitude

Added Mass Effect on Inflation

Equation of motion :

$$F = \frac{d}{dt}((m_s + a_{11})V)$$

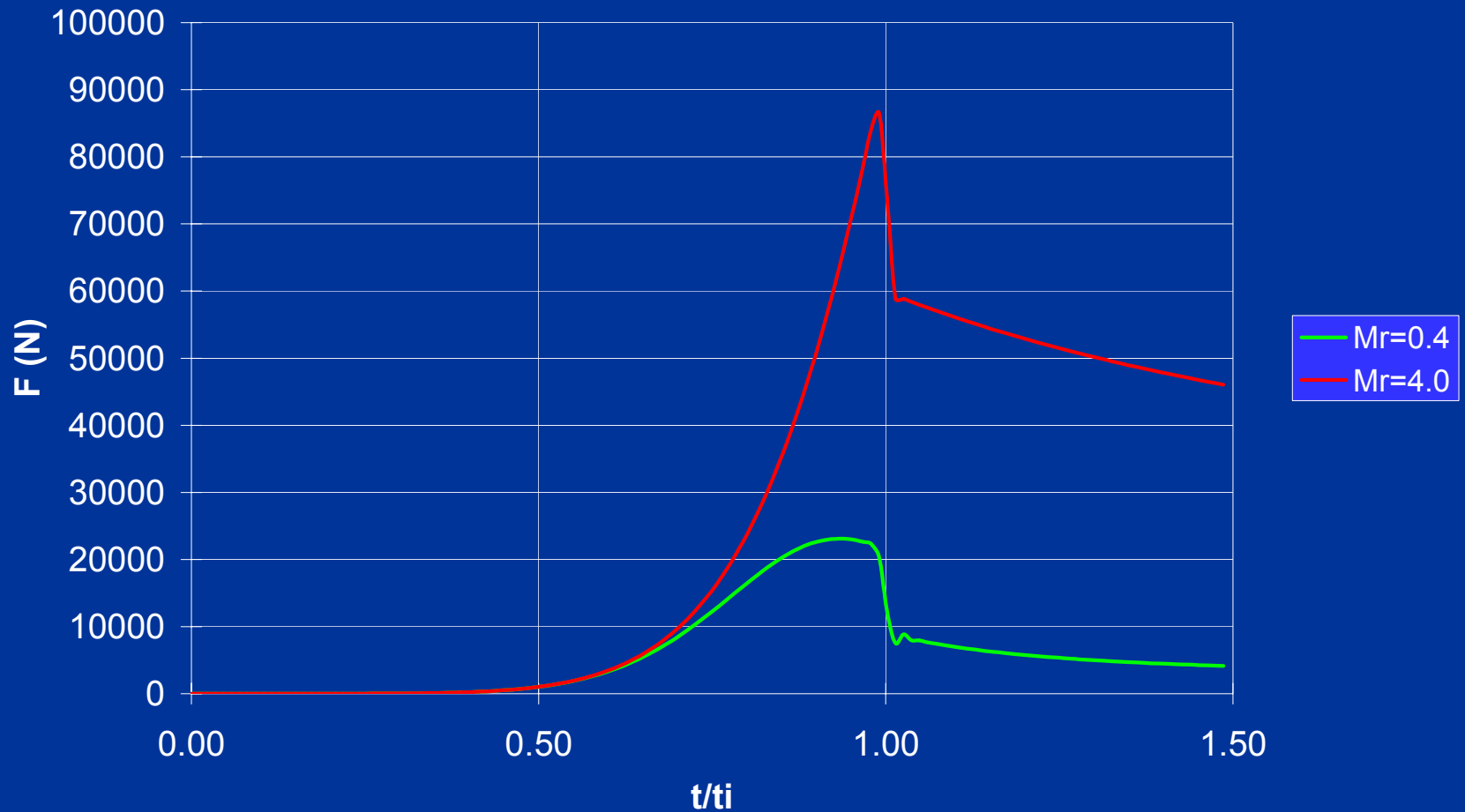
$$m_s \frac{dV}{dt} = -\frac{1}{2} \rho V^2 C_D S_p - a_{11} \frac{dV}{dt} - V \frac{da_{11}}{dt}$$

Substituting for added mass

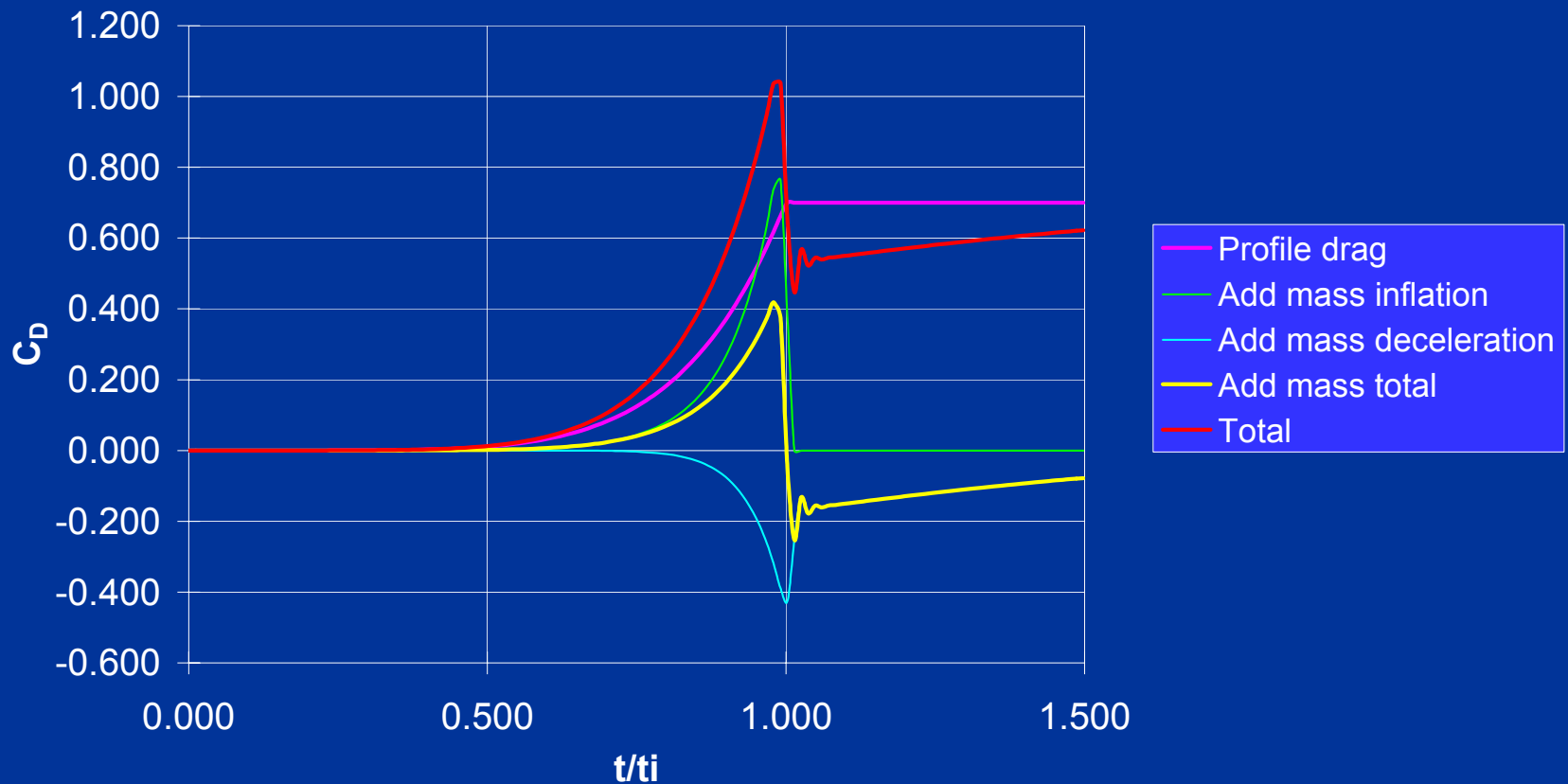
$$m_s \frac{dV}{dt} = -\frac{1}{2} \rho V^2 C_D \frac{\pi D_p^2}{4} - 2.136 \rho \frac{\pi D_p^3}{12} \cdot \frac{dV}{dt} - 2.136 \rho V \frac{\pi D_p^2}{4} \cdot \frac{dD_p}{dt}$$

During inflation for solid flat circular $D_p = D_{p \max} \left(\frac{t}{t_i} \right)^3$

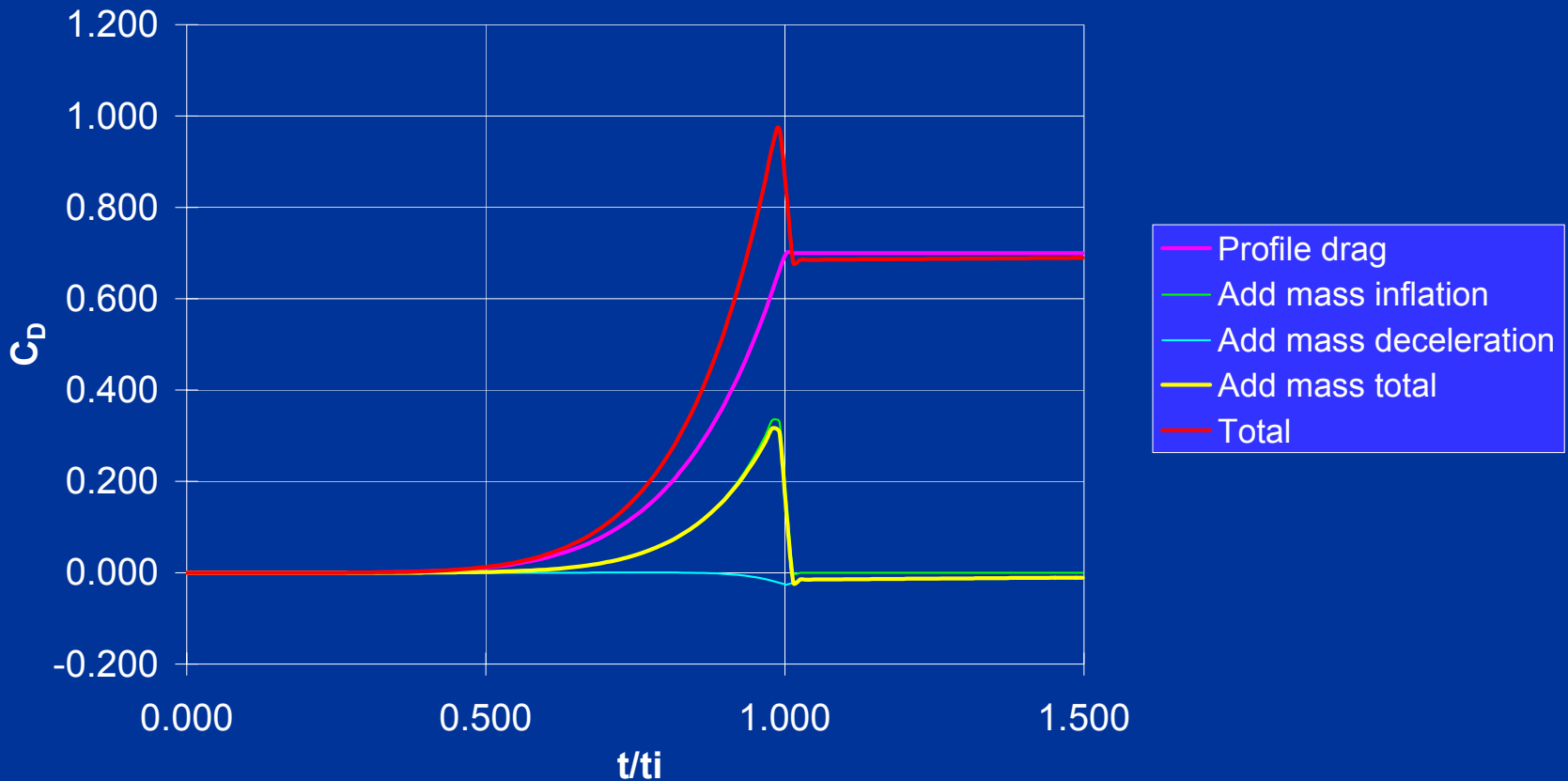
$$D_{p \max} = 0.68 D_0 \quad C_{Dp} = 1.51 \quad t_i = \frac{8.13 D_0}{V_S}$$



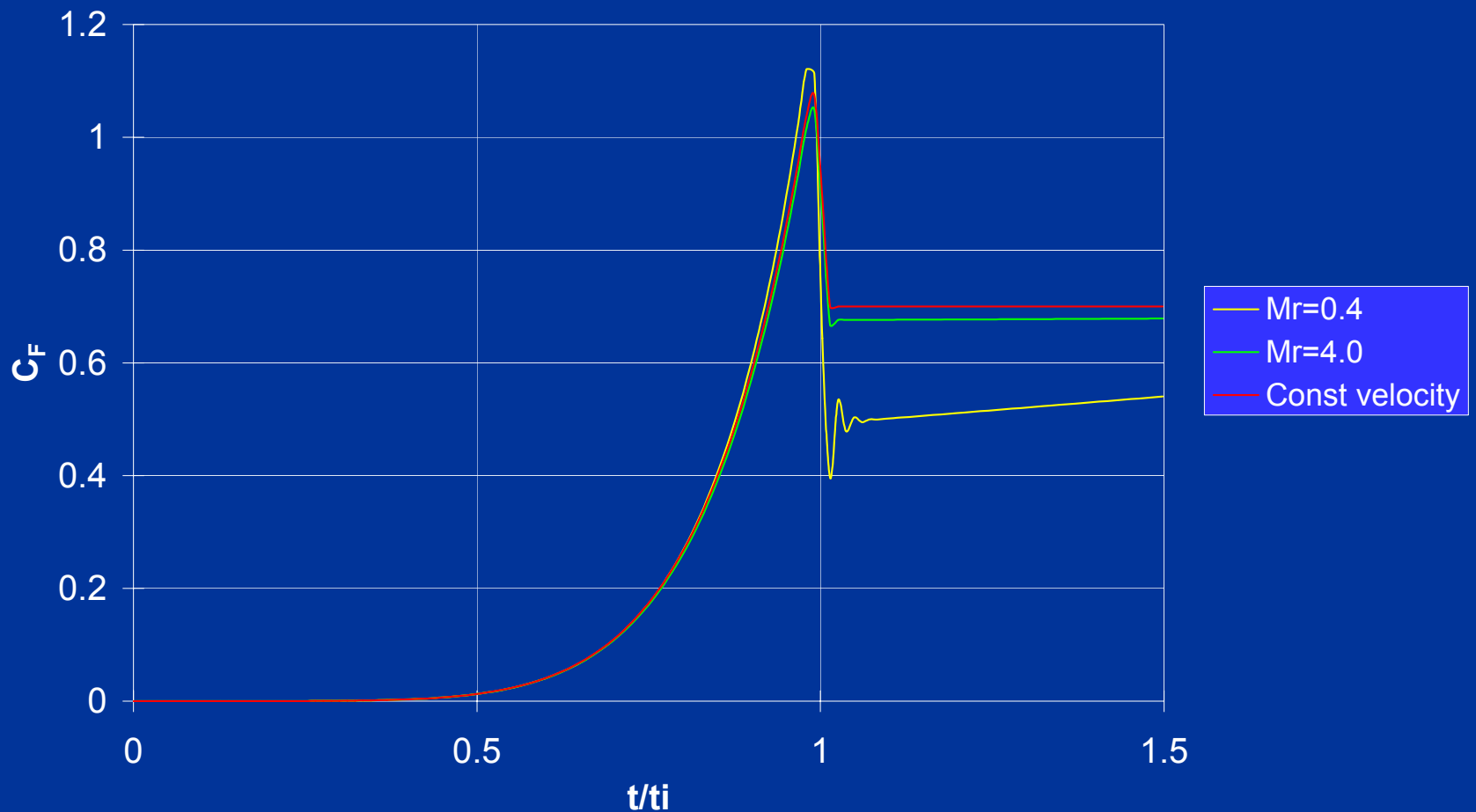
Inflation force for a flat circular parachute as a function of mass ratio



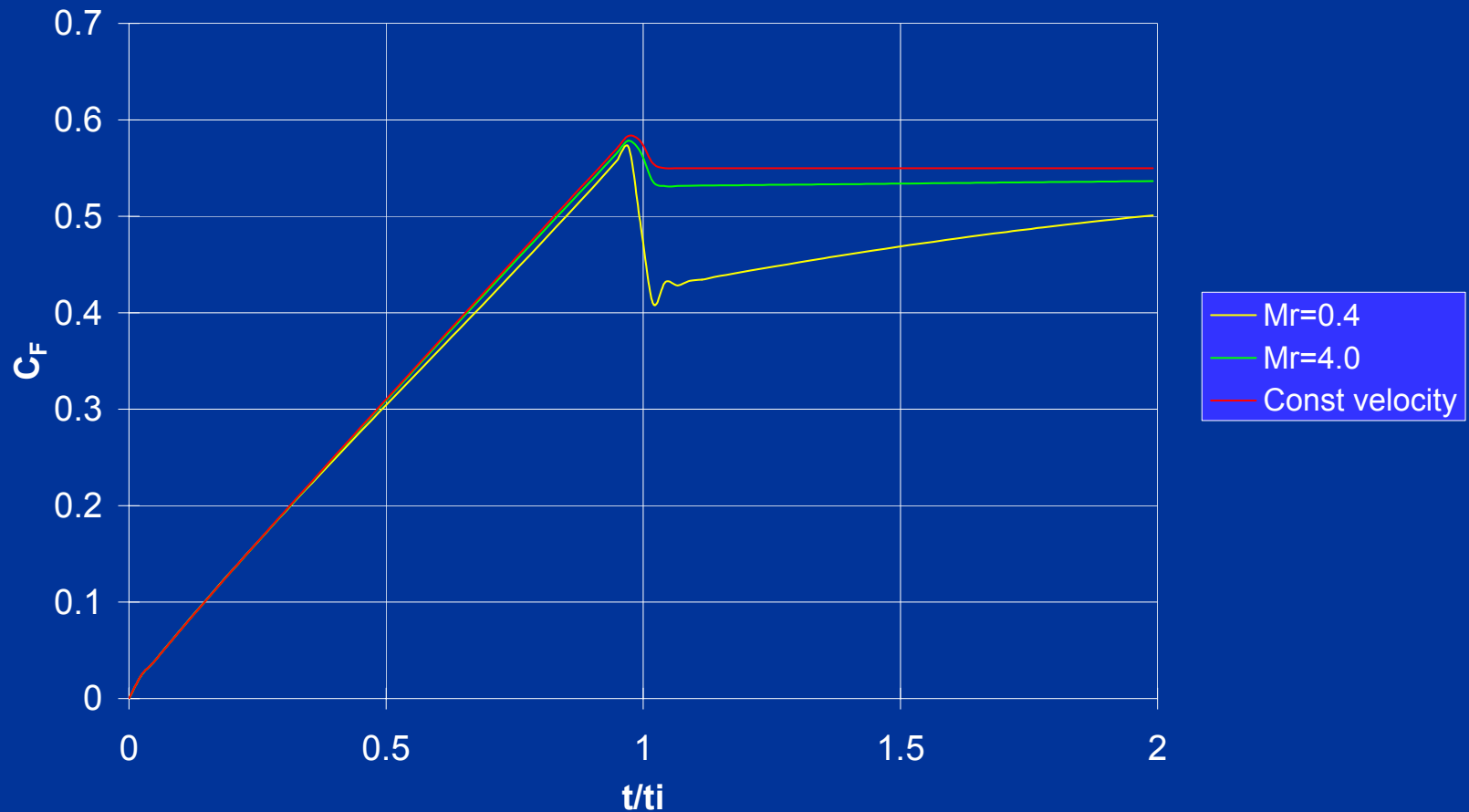
Force coefficient contributions for an inflating flat circular parachute (mass ratio 0.4)



Force coefficient contributions for an inflating flat circular parachute (mass ratio 4.0)



Total force coefficient for an inflating flat circular parachute at various mass ratios



Total force coefficient for an inflating ribbon parachute at various mass ratios

Added Mass Effect on Inflation

- ◆ Added mass largely responsible for inflation factor
 - ◆ Simple model predicts inflation factors close to experiment
 - ◆ Flat circular 1.6
 - ◆ Ribbon 1.05
- ◆ Original assumptions in simple model approximately correct – effect of added mass is in force coefficient data

Wake Recontact

- ◆ problem for ejection seat and low level weapons
- ◆ parachutes are sometimes observed to collapse shortly after full inflation
- ◆ occurs when the wake catches up with the decelerating parachute
- ◆ adverse pressure distribution causes collapse
- ◆ function of magnitude of deceleration



Wake Recontact

- Strickland proposes severity increases with increasing velocity ratio

$$\frac{V_S}{V_T} > 4.0$$

$$\frac{V_S^2}{V_T^2} = V_S^2 \cdot \frac{k\rho D_o^2}{m_s g} = k \cdot \frac{V_S^2}{D_o g} \cdot \frac{\rho D_o^3}{m_s} = k \frac{F_r}{Mr}$$

- Occurs at low mass ratios and high Froude number

Wake Recontact Cont/d

deceleration during inflation is:

$$\frac{F}{m_s g} = \frac{V_s^2}{D_o g} \cdot \frac{\pi}{8 M_r} \cdot [f(M_r, \tau)]^2 C_F(\tau)$$

wake collapse seems to occur if deceleration during inflation exceeds approximately 10g and if mass ratio is <1.0

